AD-A255 964

②

DTIC
S ELECTE
SEP 2 3 1992
C D

Optical Fibers for Long-Haul Transmission in Severe-Bending Applications

N. T. Kamikawa

92 9 22 088

92-25652

424541

19 pg

NRaD

Technical Report 1490
April 1992

Optical Fibers for Long-Haul Transmission in Severe-Bending Applications

N. T. Kamikawa

RBT

EXECUTIVE SUMMARY

OBJECTIVE

The objective of this study was to investigate the feasibility of using dual-mode optical fibers (DMFs) that would allow data transmission through 200 km of the fiber wound onto a bobbin for payout from a tethered missile.

RESULTS

Test results showed that even though the core indices of the DMFs are lower, they exhibit bending losses comparable to the single-mode fibers. The advantage of the lower core index is the potential for much lower intrinsic attenuation. The data also project further improvements in the DMF and identify desirable parameters for 200-km transmission distances. Since the DMF supports two modes, modal noise and modal dispersion can limit transmission distances. These effects were found to be negligible in the first DMF, but slightly higher in the second DMF. The confinement of the second mode determines the noise and dispersion effects.

RECOMMENDATION

Dual-mode fiber can be used over longer distances than conventional single-mode fibers and can meet the goal for 200-km transmission. If the second-order mode is loosely bound, modal noise and dispersion effects are negligible. Although tethered weapons were the initial motivation for this work, the results can be applied to fiber-optic cables for undersea surveillance systems.

CONTENTS

FIGURES

TABLE

INTRODUCTION

This report documents our investigation of an optical-fiber technique that allows data transmission through 200 km of fiber wound onto a bobbin for payout from a tethered missile. The fiber substantially improves the reliability and operational effectiveness of long standoff-range missiles by providing secure, nonline-of-sight data transmission between the missile and its launch platform. Although tethered weapons were the initial motivation for this work, the results also can be applied to fiber-optic cables for undersea surveillance systems. Transmission over these distances requires fibers with low intrinsic attenuation and reduced bending losses. Rayleigh scattering in the silica material contributes to the intrinsic attenuation, and sharp bends produce bending losses. In conventional single-mode fibers, attenuation and bending-loss requirements must be traded off to arrive at a fiber design. We found that both requirements can be met by using a technique where the second-mode cutoff is increased to wavelengths greater than the transmission wavelength. The fiber operates in a "dual-mode" regime and supports propagation of a loosely bound second mode as well as a tightly bound fundamental mode.

Transmitting data for long distances through fibers for payout systems first requires low intrinsic attenuation. Fibers with intrinsic attenuations of 0.15 dB/km (Kanamori et al., 1986) will allow the ultimate goal of >200-km data links currently pursued by the Navy's air-launched weapons programs. While the total attenuation of 30 dB in the data link is within today's capability for laser transmitters and avalanche photodiode receivers, additional losses (e.g., from peel-point bends during payout) will reduce the length of the usable data link. For each dB of excess loss, a range penalty of 7 km will be incurred.

Figure 1 depicts the performance levels of the fibers used in payout systems. Telecommunication (telco) and dispersion-shifted fibers fall short of the bending-loss performance required of these fibers, although their intrinsic attenuations were quite good. Single-mode fibers specifically designed to meet the bending-loss requirement (payout fibers) exhibited high intrinsic attenuations because of the higher dopant levels required, but were still useful in shorter range systems. The goal of this work is to develop the fiber designs that would allow the intrinsic attenuation to again be lowered to 0.15 dB/km while keeping bending losses to a minimum (1 dB).
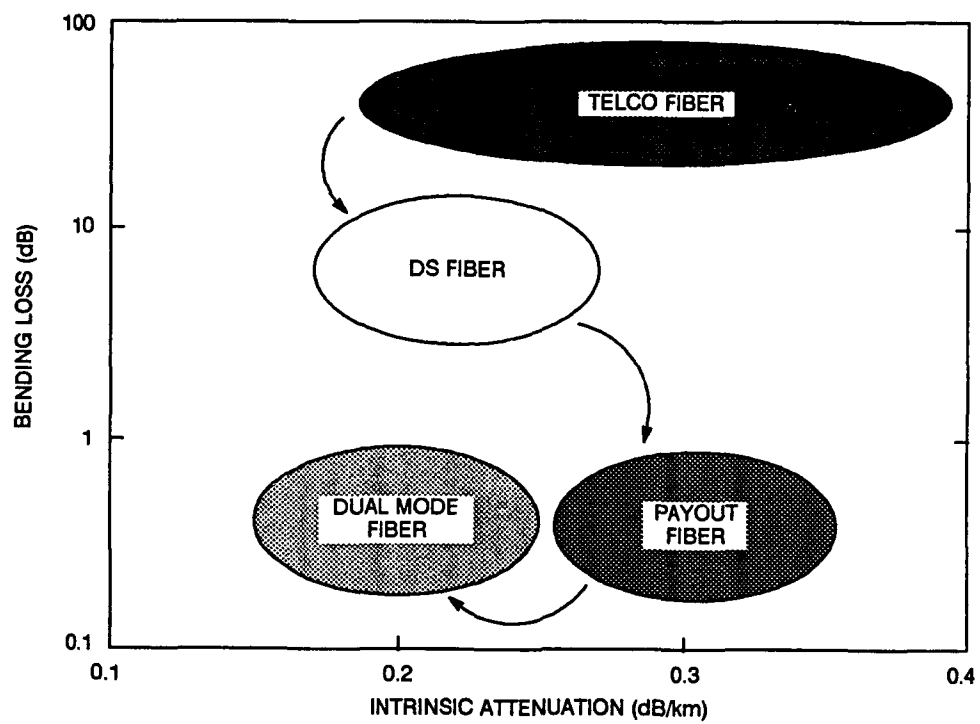
Figure 1. The evolution of fiber specifications for missile tethers.

DMF DESIGN

The designs for the DMF evolved from the high, single-mode fibers (payout fiber in figure 1) that meet the bending-loss requirements for missile tethers, but exhibit intrinsic attenuations that are too high for 200-km transmission. (Δ is the relative refractive-index difference between the core and cladding.) The Δ in these single-mode fibers is increased to 0.9 percent to confine the mode field tightly to the core and reduce bending losses (Starkey & Suggs, 1988; Kamikawa, Rast, & Chang, 1988). In comparison, the Δ in a telco fiber is only 0.3 percent. The approach in the DMF design was to decrease Δ in the high single-mode fibers and to increase λ_c to maintain the same bending-loss performance. The higher λ_c also confines the mode tightly to reduce bending losses. The advantage of the lower DMF is that lower-Δ levels of germanium dopants are required in the core, which reduces Rayleigh scattering. Rayleigh scattering is a major contributor to the fiber's intrinsic attenuation.

From early theory, a fiber's bending loss is described by

$$\alpha = (A_c \sqrt{R}) \exp(-UR) \quad , \tag{1}$$

where α is the bending loss in dB/mm, R is the bending radius in mm, and A_c is determined by the normalized intensity at the core-cladding interface. The U in the exponential determines a fiber's performance in bending and is given by

$$U - (0.705/\lambda)(\Delta n_{ci})^{3/2}[2.748 - 0.996(\lambda/\lambda_c)]^3 \quad , \tag{2}$$

where n_{ci} is the refractive index of the cladding (Jeunhomme, 1983). Equation (2) shows that U is dependent on the fiber's λ_c and Δ. Figure 2 shows a plot of two contours of constant bending loss corresponding to U values of 2 and 3. In theory, all fibers with λ_c and Δ combinations that fall on a particular contour will exhibit the same bending loss. Points labeled C and D are the high-Δ, low-bending-loss, single-mode fibers. Thus, moving to the right of the plot on the $U = 3$ contour clearly allows a different set of λ_c and Δ values to be selected and still achieves the same bending-loss e.

The points labeled A and B represent the fiber parameters used in this investigation. A summary of the four fibers' parameters is shown in table 1. Also shown in figure 2 is a telco single-mode fiber (fiber E) with a much lower U value so that poor bending-loss performance is expected.

Fibers A and B were fabricated by Lightwave Technology, Inc., in Chatsworth, CA, using an outside vapor-deposition technique. The cores were doped with germanium to raise the refractive index above the cladding index. An intrinsic attenuation in fiber A of 0.30 dB/km at 1550 nm was slightly higher than expected because the lower Δ required lower depart levels. An attenuation closer to 0.25 dB/km was expected. This can occur in developmental fibers where the fabrication process is not optimized, and absorption losses add to the Rayleigh scattering to increase the intrinsic attenuation. However, this does not diminish from the potential for lower intrinsic attenuation allowed by a lower Δ.
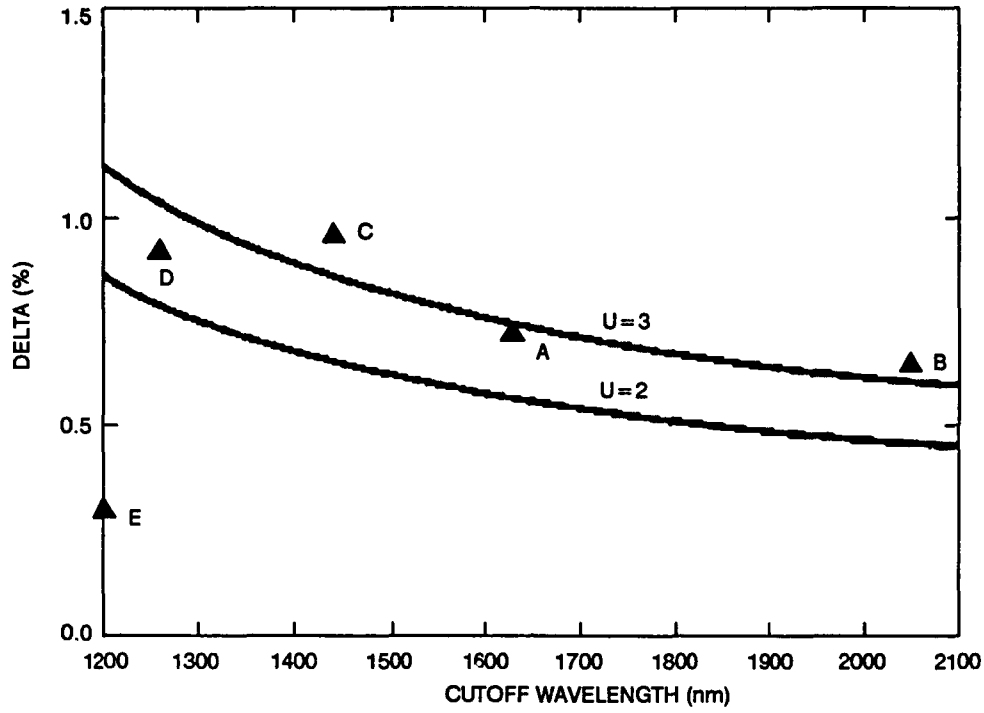
Figure 2. The design model at $\lambda = 1550$ nm relating Δ, λ_c, and U.

Table 1. All of the fibers are step-index, matched-clad. λ_c is the effective cutoff wavelength of the LP_{11} mode, and Δ is the core-clad refractive-index difference.

Fiber	A	B	C	D	E
λ_c (nm)	1630	2052	1438	1259	1200
Δ (%)	0.72	0.65	0.96	0.92	0.31

TEST RESULTS

BENDING LOSS AND INTRINSIC ATTENUATION

Bending tests were devised to verify the designs of the two DMFs. The test setup included a static fixture that bends the fiber to simulate the peel-point bend radius, and an optical instrument that measures the loss between 1300 and 1600 nm. The bending radius requirement was derived by observing the peel point on the bobbin during payout. Fiber bends were observed less than 90° from the direction of the wind with a radius as small as 2 mm. Figure 3 displays the results of the bending loss tests at 1550 nm. The results show that both the DMF and high-Δ single-mode fibers meet the requirement for <1-dB loss for the 2-mm bend. The results also show that the losses in fiber A are between the losses in fibers C and D, as predicted in figure 2. Fiber B exhibits losses that are lower than the losses in fibers A and D, which is also predicted in figure 2. The bending losses in fiber E are plotted to emphasize the poor bending performance of telco fibers in this application.
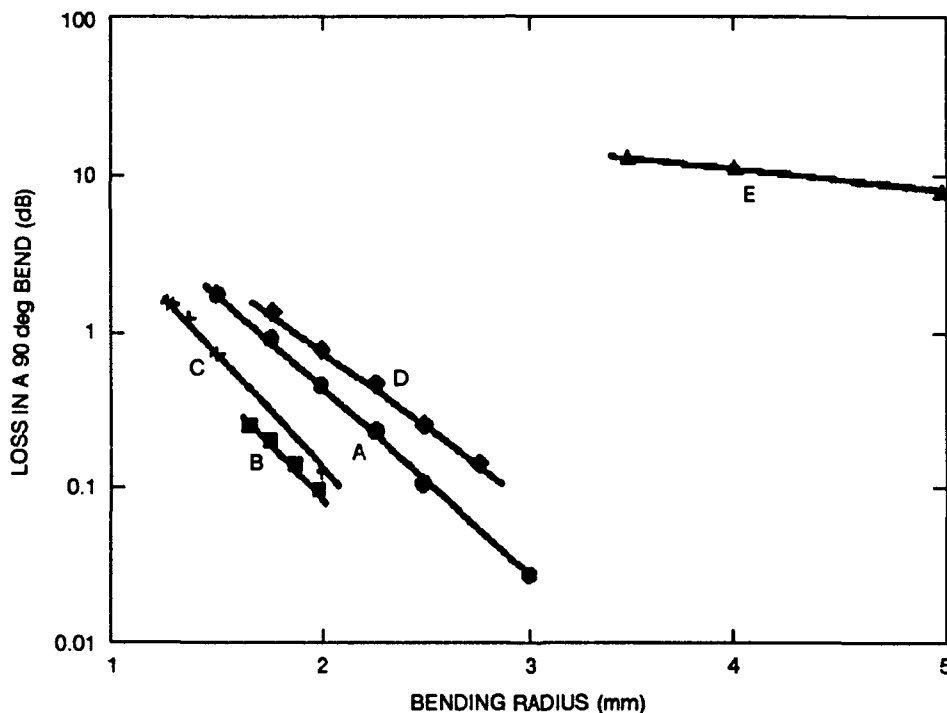
Figure 3. Losses at λ = 1550 nm in a 90° bend.

Having shown that the DMFs meet the bending-loss requirement for a 90° bend with a 2-mm radius, the intrinsic attenuations were analyzed. The intrinsic attenuations of fibers A and B were measured to be 0.30 dB/km and 0.22 dB/km, respectively, at λ = 1550 nm. These values are less than the nominal attenuations of 0.35 dB/km for the high-Δ fibers. The reduced Rayleigh scattering in the DMF is the principal reason for the lower attenuation. The lower germanium dopant concentration required for the lower Δ produces

5

lower Rayleigh scattering. However, the maximum transmission distance fiber B can achieve with an attenuation of 0.22 dB/km is 136 km, assuming an optical loss budget of 30-dB. This is still short of the 200-km goal. The application of pure-silica core technology provides a method to achieve the 200-km goal. This technique uses fluorine dopants to depress the cladding index to avoid doping the core with germanium. With an undoped, pure-silica core, attenuations as low as 0.15 dB/km have been reported (Kanamori et al., 1986). This fiber meets the 30-dB budget in a 200-km distance. However, the largest Δ reported to date in pure-silica core fibers is only 0.73 percent (Urano et al., 1989), as opposed to the 1 percent achievable with germanium doping of the core. The Δ for both DMF are less than 0.73 percent so that fabricating fiber A or B with pure-silica cores will produce fibers that meet intrinsic attenuation as well as the bending-loss requirements for the 200-km goal.

MODAL NOISE AND MODAL DISPERSION

Fibers A and B support both the fundamental LP_{01} mode and a higher-order LP_{11} mode, since λ_c is greater than the operating wavelength of 1550 nm. Modal noise occurs when the two modes interfere coherently in a connector or splice resulting in distortions in the signal amplitude. The magnitude of this distortion depends on the relative power between the two modes. Bit-error rate tests on fiber A revealed negligible amounts of modal noise. Figure 4 shows the results, indicating a power penalty of only 0.3 dB due to modal noise. The lack of modal noise is due to a low fraction of the total power propagating in the LP_{11} mode. The power in the LP_{11} mode is low because its attenuation is high, the LP_{01} mode is preferentially launched at the transmitter end, and mode coupling is low. Even a poor splice of 1.5-dB loss inserted in the fiber failed to couple significant amounts of power from the LP_{01} to the LP_{11} mode. Far-field intensity measurements of the two modes taken 2 meters downstream from the 1.5-dB splice shown in figure 5 indicate that mode coupling is low. Splices made with an arc fusion splicer normally exhibit losses less than 0.1 dB, thus assuring negligible coupling between the modes.

Modal dispersion is an issue in DMF since the group velocities of the two modes are different. The difference in velocities will cause the two modes to be received at different times after propagating the 200-km distance. This distorts the optical signal and limits bandwidth. Sufficiently long lengths of fiber A were not available to directly measure modal dispersion. Instead, the spectral attenuations of the two modes were measured to assess the likelihood of modal dispersion. The spectral attenuations are shown in figure 6. While the attenuation of the LP_{01} mode is less than 0.30 dB/km at 1550 nm, the attenuation of the LP_{11} mode is 300 dB/km. The LP_{11} mode is severely attenuated because it is loosely bound to the core. Even if small amounts of power are coupled from the LP_{01} to LP_{11} modes in a poor splice or misaligned connector, the LP_{11} mode is attenuated by 30 dB after only 100 meters of transmission. This precludes modal dispersion in fiber A.

The LP_{11} mode in fiber B is much more tightly bound due to the higher λ_c. Consequently, the modal-noise power penalty is 1.5 dB, which is too large for the 200-km transmission distance.
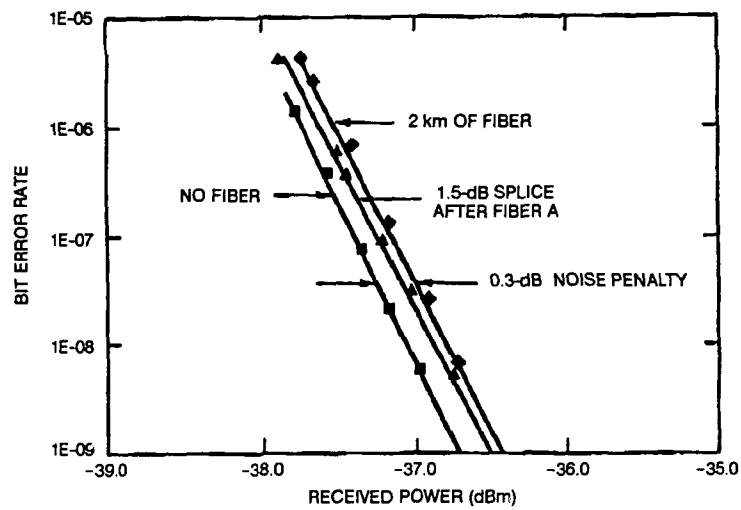
6

Figure 4. Bit-error-rate measurements for fiber A at a
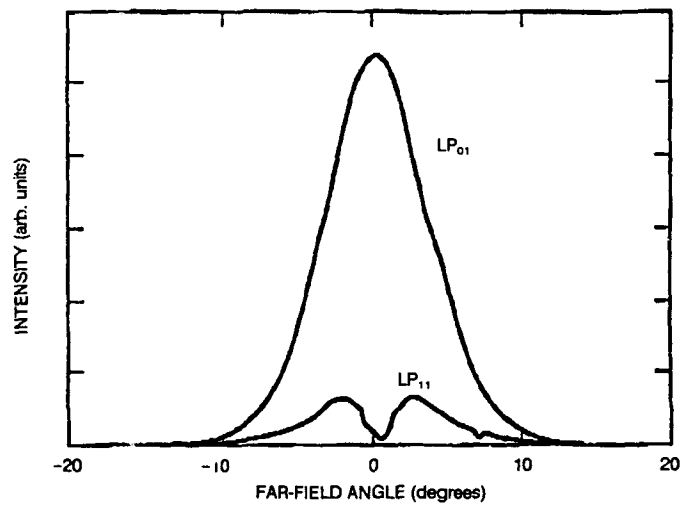data rate of 200 Mbps and $2^{20}-1$ pseudorandom pattern.

Figure 5. Far-field intensity measurements 2 meters
from a 1.5-dB splice.
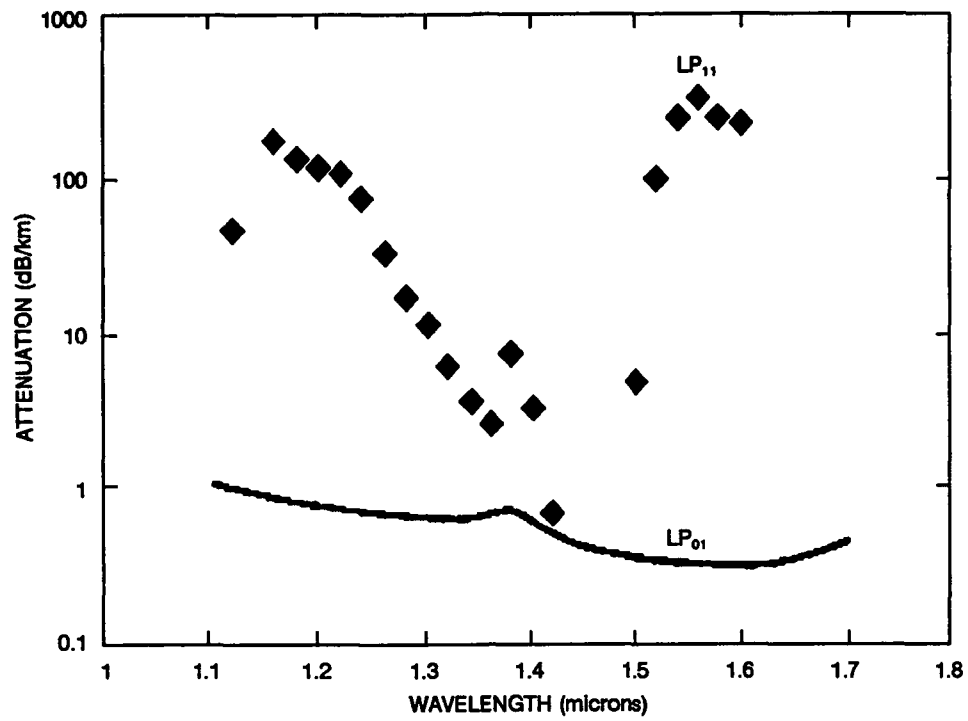
Figure 6. Spectral attenuation of the LP_{01} and LP_{11} modes.

SUMMARY

We have shown that bending losses in DMFs are comparable to high-Δ single-mode fibers, but with much lower intrinsic attenuation to permit longer transmission distances. Bending loss and attenuation are critical requirements in high-bending applications, such as data links for long standoff-range missiles and cables in undersea surveillance systems. When the dual-mode fiber is fabricated with a pure-silica core, transmission distances of 200 km are predicted. Modal noise and dispersion in DMFs were also investigated and found to be negligible for fibers when the second-order mode is loosely bound.

9

REFERENCES

Jeunhomme, L. B. 1983. *Single-Mode Fiber Optics Principles and Applications*, Marcel Dekker, Inc., p. 91.

Kamikawa, N. T., H. E. Rast, and C. T. Chang. 1988. "Fiber for Air-Deployed High-Speed Payout Links," *DoD Fiber Optics Conference '88, Conference Record*, pp. 186–187, March 1988.

Kanamori, H., H. Yokota, G. Tanaka, and M. Watanabe. 1986. "Transmission Characteristics and Reliability of Pure-Silica-Core Single-Mode Fibers," *Journal of Lightwave Technology*, vol. LT4, no. 4, pp. 1144–1150.

Starkey, T. C., and J. W. Suggs. 1988. "Reduced Mode-Field Diameter Single-Mode Fiber for Specialty Applications," *Proceedings of the International Wire and Cable Symposium*, pp. 1517, November 1988.

Urano, A., Y. Ichiguro, M. Shigematsu, and H. Kanamori. 1989. "Pure Silica Core Dispersion Shifted Single-Mode Fibers," *13th European Conference on Optical Communication*, pp. 175–178, September 1987.

REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE April 1992	3. REPORT TYPE AND DATES COVERED Final FY 90—FY 91

4. TITLE AND SUBTITLE
OPTICAL FIBERS FOR LONG-HAUL TRANSMISSION IN SEVERE-BENDING APPLICATIONS

5. FUNDING NUMBERS
PE: 602936N
WU: DN300042
PR: ZE93

6. AUTHOR(S)
N. T. Kamikawa

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Command, Control and Ocean Surveillance Center (NCCOSC)
RDT&E Division (NRaD)
San Diego, CA 92152-5000

8. PERFORMING ORGANIZATION REPORT NUMBER
NRaD TR 1490

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of the Chief of Naval Research–20T
800 N. Quincy St.
Arlington, VA 22217–5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

An optical-fiber technique is investigated that allows data transmission through 200 km of dual-mode optical fibers wound onto a bobbin for payout from a tethered missile. The study shows that the dual-mode fibers can be used over longer distances than conventional single-mode fibers and can meet the goal for 200-km transmission. The design of the dual-mode fibers is discussed, and test data are presented on their bending loss. Results from modal-noise and modal-dispersion tests are also given, showing that modal-noise and modal-dispersion effects are negligible, if the second-order mode is loosely bound.

14. SUBJECT TERMS
fiber optics
microbending loss
cutoff wavelength
dispersion
mode coupling

15. NUMBER OF PAGES
19

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

21a. NAME OF RESPONSIBLE INDIVIDUAL	21b. TELEPHONE *(include Area Code)*	21c. OFFICE SYMBOL
N. T. Kamikawa	(808) 257–1165	Code 534

INITIAL DISTRIBUTION

Code	Name	
Code 0012	Patent Counsel	(1)
Code 014	W. T. Rasmussen	(1)
Code 0142	K. Campbell	(1)
Code 0144	R. November	(1)
Code 144	V. Ware	(1)
Code 425	A. Nakagawa	(1)
Code 50	H. O. Porter	(1)
Code 53H	D. W. Murphy	(1)
Code 534H	N. Kamikawa	(25)
Code 534H	G. Tanaka	(1)
Code 534H	J. Holzschuh	(1)
Code 55	H. E. Rast	(1)
Code 553	D. Albares	(1)
Code 555	M. McLandrich	(1)
Code 714	K. Rogers	(1)
Code 7502	R. Walker	(1)
Code 808	R. Peterson	(1)
Code 82	R. J. Kochanski	(1)
Code 946	M. Brininstool	(1)
Code 946	S. Cowen	(1)
Code 952B	J. Puleo	(1)
Code 961	Archive/Stock	(6)
Code 964B	Library	(2)

Defense Technical Information Center
Alexandria, VA   22304-6145   (4)

Center for Naval Analyses
Alexandria, VA   22302-0268

Naval Air Systems Command
Washington, DC   20361-0001

Naval Air Warfare Center
Weapons Division
China Lake, CA   93555-6001   (2)

Naval Undersea Warfare Center
 Detachment
New London, CT   06320

Naval Surface Warfare Center
Dahlgren Division
Dahlgren, VA   22448-5000

Naval Postgraduate School
Monterey, CA   93943

U. S. Army CECOM
Fort Monmouth, NJ   07703

NIST
Boulder, CO   80303

NCCOSC Washington Liaison Office
Washington, DC   20363-5100

Navy Acquisition, Research & Develop-
   ment Information Center (NARDIC)
Washington, DC   20360-5000

Naval Air Warfare Center
Point Mugu, CA   93042

Naval Sea Systems Command
Washington, DC   20362-5101

Naval Research Laboratory
Washington, DC   20375-5000

Space & Naval Warfare Systems Command
Washington, DC   20363-5100

Office of Naval Technology
Arlington, VA   22217-5000

U. S. Army MICOM
Redstone Arsenal, AL   35898

U. S. Air Force RADC
Griffiss AFB, NY   13441